CP violation in the Bs system

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Outline

- Important CDF/DØ detector/trigger features

- Measurement of DCPV in $B^0_s \rightarrow K^-\pi^+$ (CDF)

- $\Delta\Gamma_s$ and ϕ_s measurements in $B^0_s \rightarrow J/\psi\phi$ (DØ/CDF)

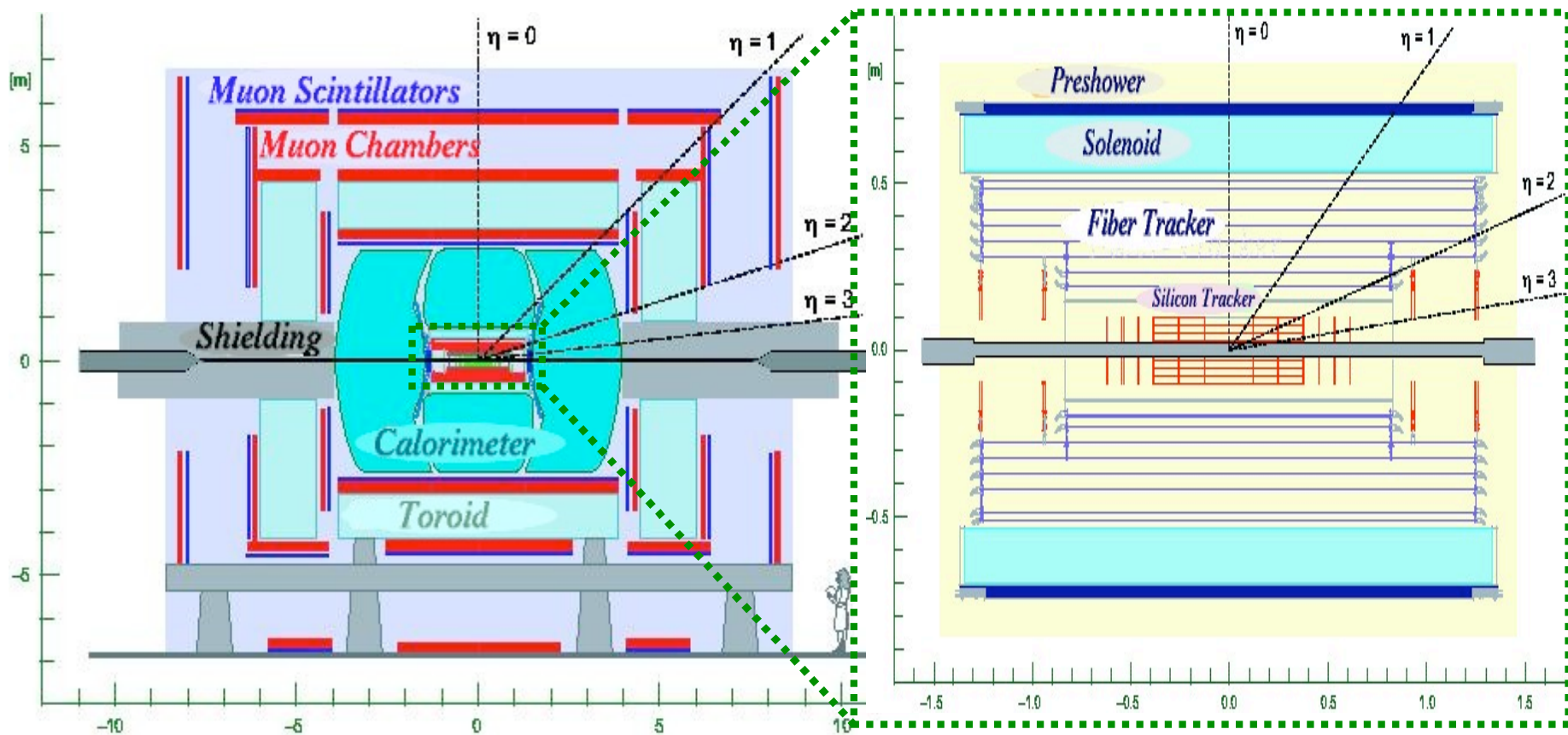- Dimuon/single muon charge asymmetry (DØ)

- Conclusions

Important CDF features

- Central Drift chamber in B field

  - $\sigma(p_T)/p_T{}^2 \sim 0.1\%$ GeV/c^{-1}
    (excellent tracking & mass resolution)

  - dE/dx measurement

- Silicon VerteX detector

  - I.P. resolution: 35 μm @2GeV/c

- Time-of-Flight detector

- Muon coverage $|\eta| < 1$

- Hadronic B triggers
  - L1: 2D tracks in COT, $p_T > 2.0$ GeV/c
  - L2: 2D tracks in COT+SVX, $p_T > 2.0$ GeV/c
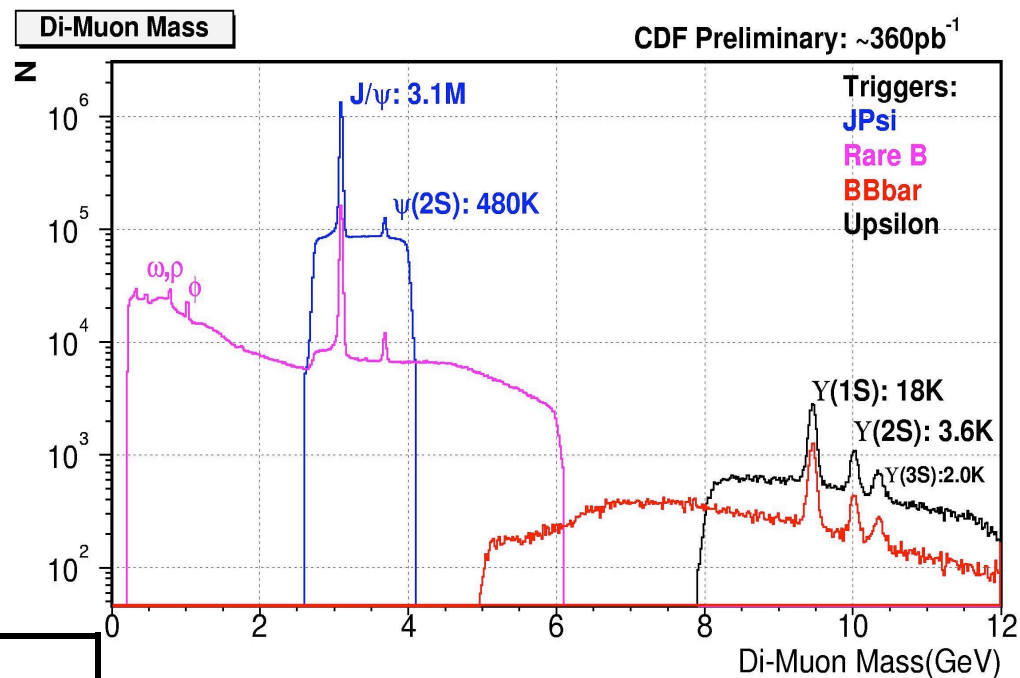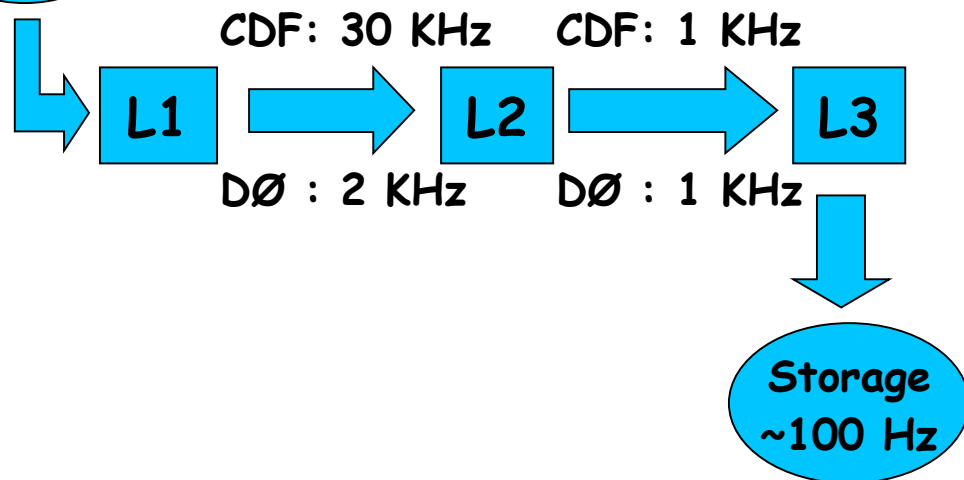   Offline quality I.P. measurement
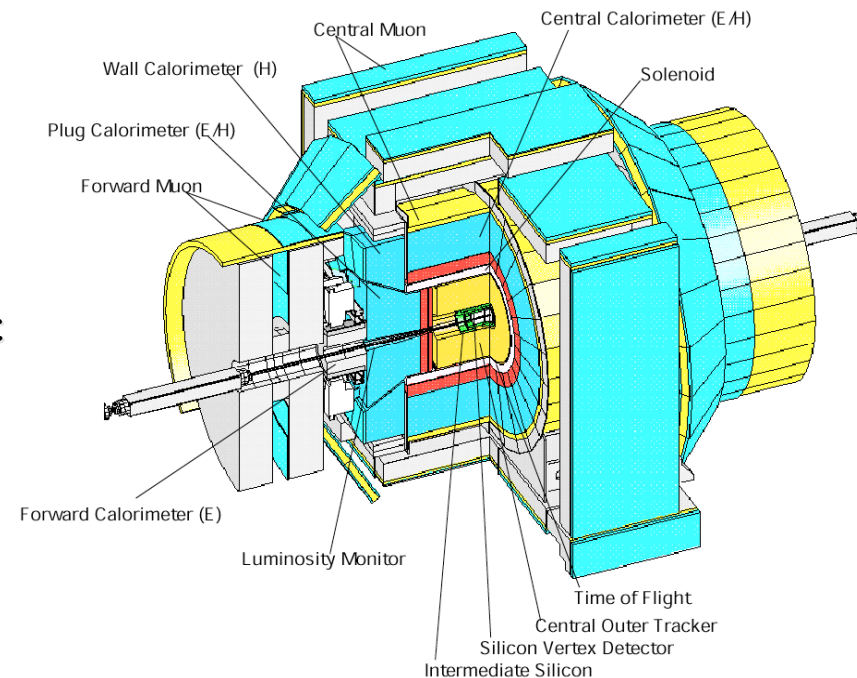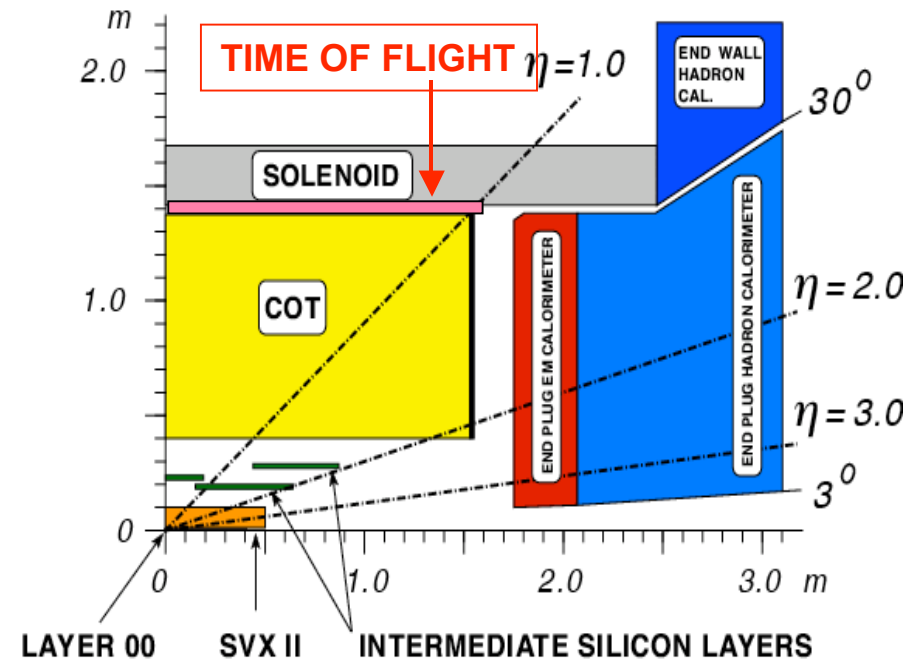
Important DØ features

- Excellent coverage of Tracking and Muon system ($|\eta|<2$)

- Excellent calorimetry and electron identification

- High efficiency muon trigger with p_T measurement at L1 by toroids

- 2 T Solenoid & 1.8 T Toroid polarity reversed weekly (reduce sensitivity to detector geom.)
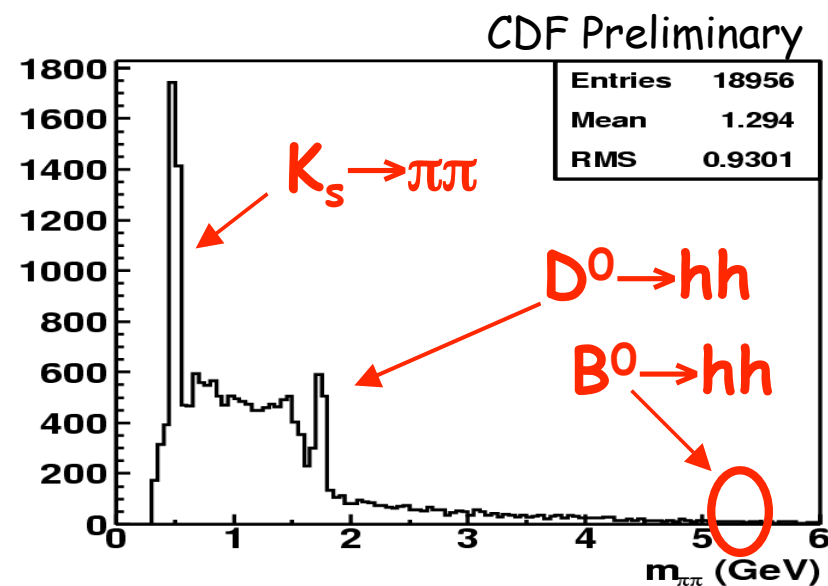
CDF/DØ B triggers

Data In 1.7 MHz

CDF: 30 KHz → **L1** → CDF: 1 KHz

DØ : 2 KHz → **L2** → DØ : 1 KHz → **L3**

Storage ~100 Hz

Di-Muon Mass

CDF Preliminary: ~360pb^{-1}

Triggers:
JPsi
Rare B
BBbar
Upsilon

ω,ρ
ϕ
J/ψ: 3.1M
ψ(2S): 480K
Υ(1S): 18K
Υ(2S): 3.6K
Υ(3S):2.0K

Di-Muon Mass(GeV)

Trigger	CDF	DØ
2-Track	p_T > 2.0 GeV/c $p_{T1}+p_{T2}$ > 5.5 GeV/c 100 μm<$|d_{1,2}|$< 1 mm	—
1-Muon	—	$p_T (\mu)$>3,4,5 GeV/c
2-Muon	$p_T(\mu's)$ > 1.5 GeV/c	$p_T(\mu's)$>2.0 GeV/c

CDF Preliminary

Entries	18956
Mean	1.294
RMS	0.9301

$K_s \rightarrow \pi\pi$

$D^0 \rightarrow hh$

$B^0 \rightarrow hh$

$m_{\pi\pi}$ (GeV)

Measurement of the Direct CPV in $B^0_s \to K^-\pi^+$

$B^0_{(s)} \to h^+ h'^-$ sample selection

Reject light-quark background |

Two oppositely-charged tracks

Transverse opening angle [20º, 135º]

p_{T1}, p_{T2} > 2 GeV
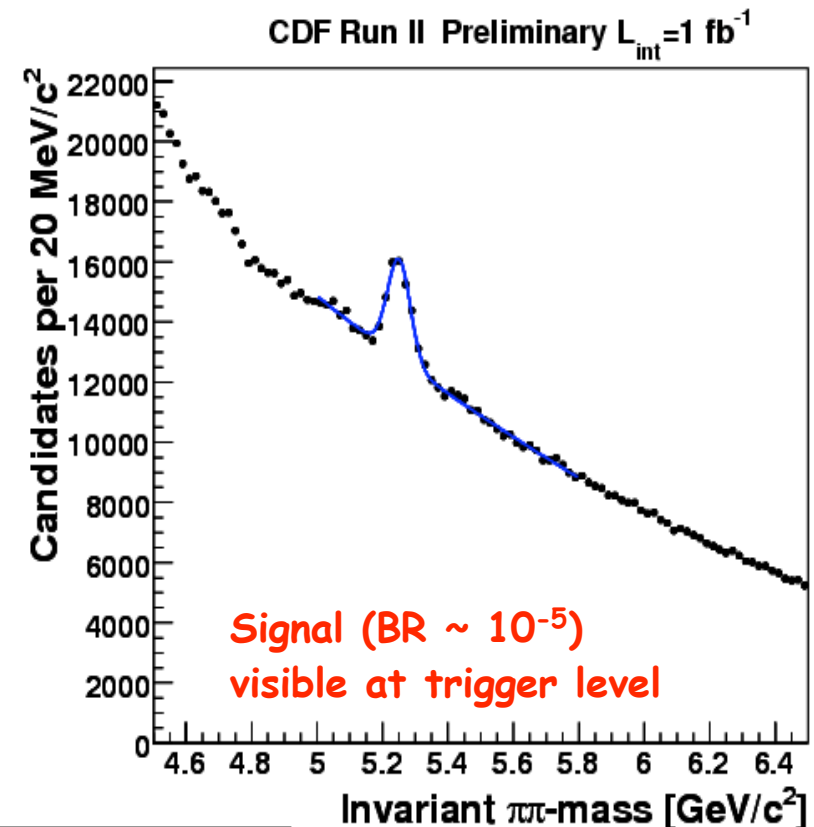
$p_{T1} + p_{T2}$ > 5.5 GeV

Long-lived candidate

Track impact parameters > 100 μm

Transverse decay length L> 200 μm

B impact parameter < 140 μm

CDF Run II Preliminary L_{int}=1 fb^{-1}

Signal (BR ~ 10^{-5}) visible at trigger level

Invariant $\pi\pi$-mass [GeV/c^2]

Tighten trigger cuts and add further observables | OFFLINE cuts
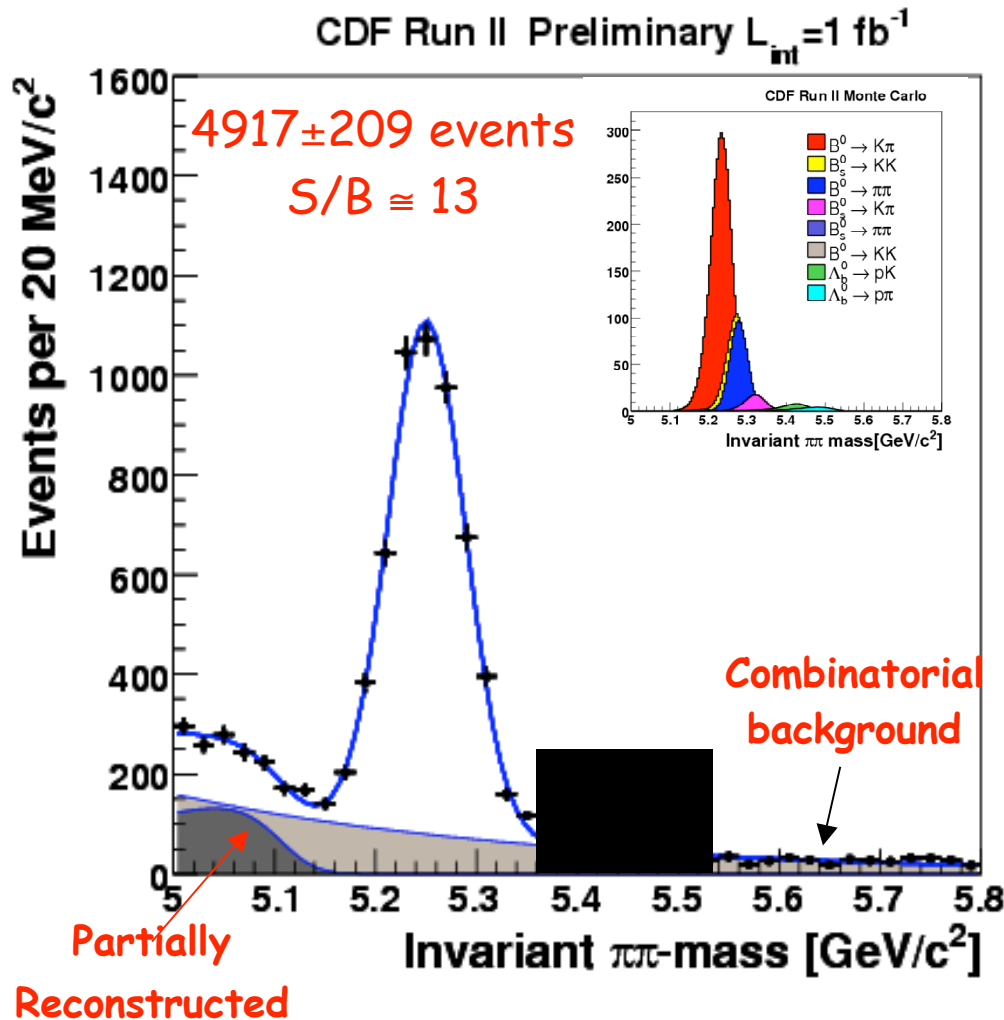
3D Vertex chi-square

B Isolation: $$I(B)= \frac{Pt(B)}{Pt(B) + \Sigma_{cone}Pt_i}$$

Effective in reducing light-quark background and 85% efficient

$B^0_{(s)} \to h^+h'^-$ offline signal

CDF Run II Preliminary $L_{int}=1\,fb^{-1}$

4917±209 events
S/B ≅ 13

Combinatorial background

Partially Reconstructed

Despite good mass resolution (≅22MeV/c²) $B^0 \to K\pi$, $B^0 \to \pi\pi$, $B^0_s \to KK$, $B^0_s \to K\pi$ overlap in a single peak (~35 MeV/c²)

Note that the use of a single mass assignment ($\pi\pi$) causes overlap even with perfect resolution

Blinded region of unobserved modes $B^0_s \to K\pi$, $B^0_s \to \pi\pi$, $\Lambda^0_b \to p\pi/pK$

Need to determine signal composition with a Likelihood fit, combining information from kinematics (mass and momenta) and particle ID (dE/dx).

Separating channels

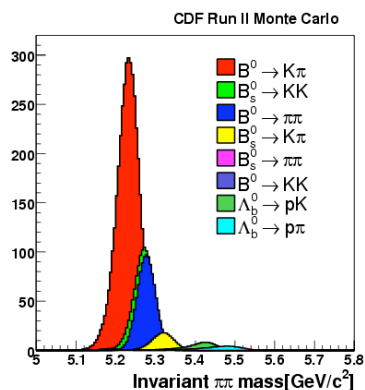Unbinned ML fit based on 5 observables (kinematics+PID)

$$\mathscr{L}(\vec{\theta}) = \prod_{i=1}^{N} \mathscr{L}_i(\vec{\theta})$$

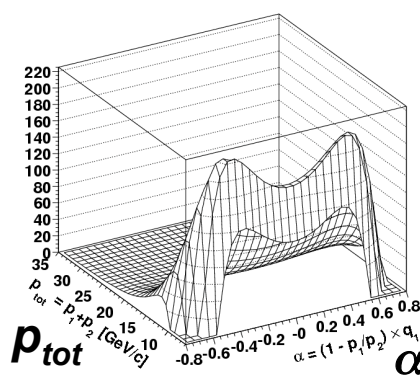fraction of jth mode, to be determined by the fit

$$\mathscr{L}_i(\vec{\theta}) = (1-b)\sum_j f_j \mathscr{L}_j^{\mathrm{sign}} + b\mathscr{L}^{\mathrm{bckg}}$$

$$pdf_j^{\mathrm{m}}(m_{\pi\pi}|\alpha, p_{tot}; \vec{\theta}) \cdot pdf_j^{\mathrm{p}}(\alpha, p_{tot}; \vec{\theta}) \cdot pdf_j^{\mathrm{PID}}(\mathrm{ID}_1, \mathrm{ID}_2|p_{tot}, \alpha; \vec{\theta})$$
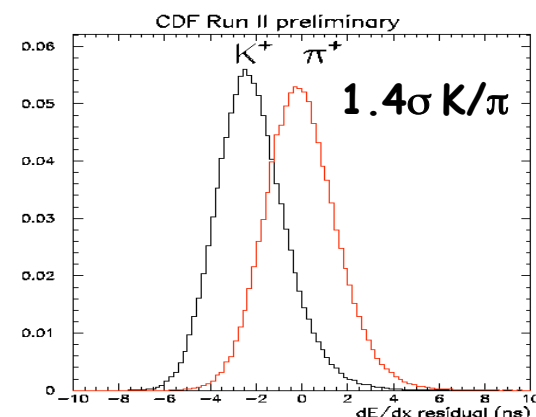

mass term

momentum term
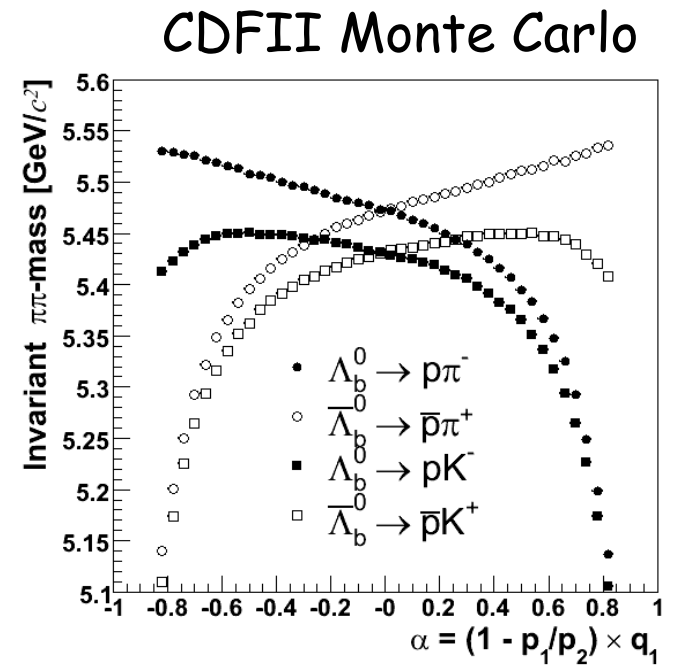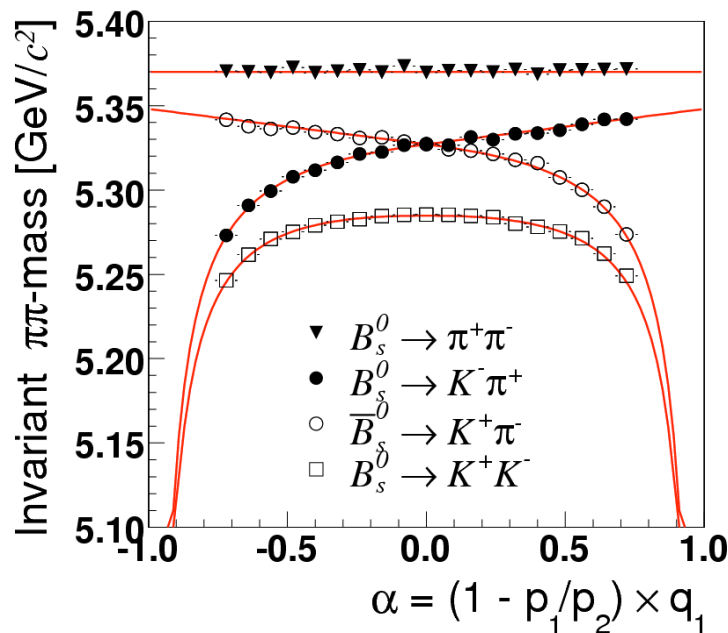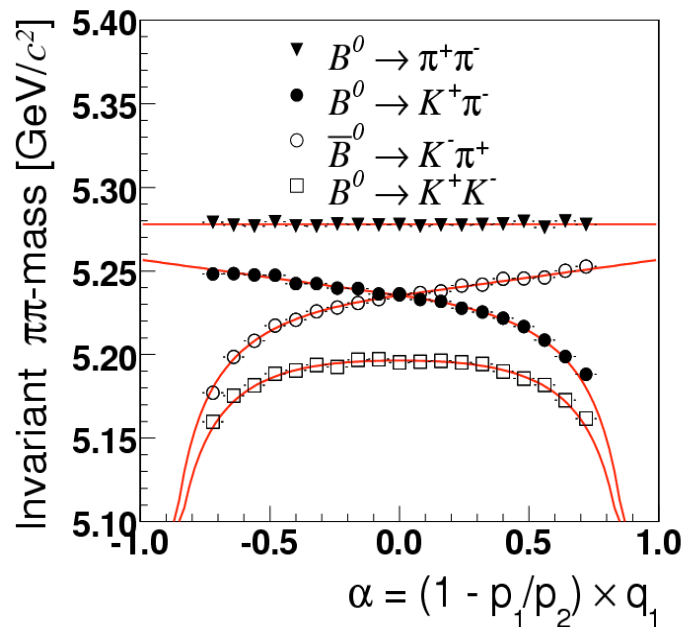
dE/dx term

Signal shapes: from MC and analytic formula
Background shapes: from data sidebands

sign and bckg shapes
from $D^0 \to K^-\pi^+$

Handle 1: track momenta

CDFII Monte Carlo

Kinematic variables:

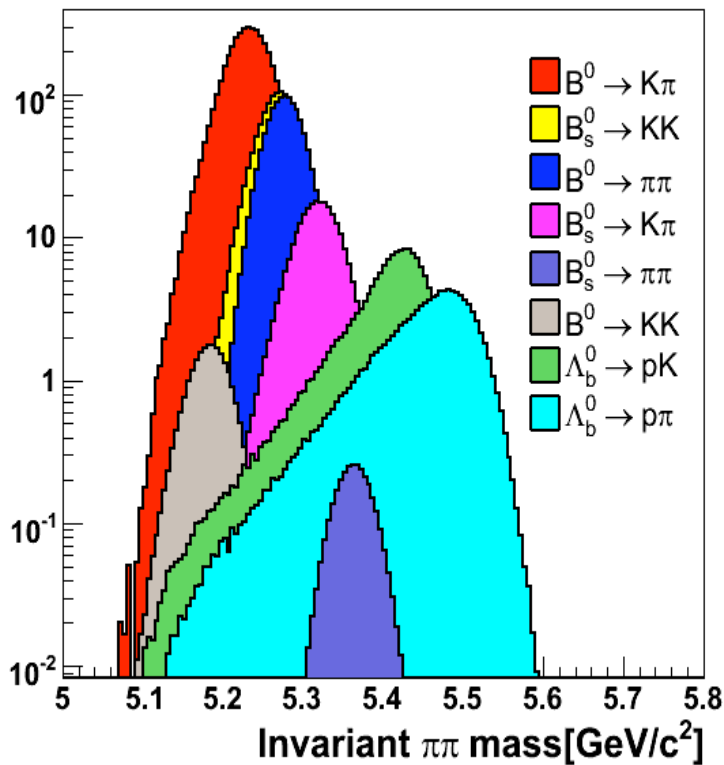p_{min} (p_{max}) is the 3D track momentum with $p_{min} < p_{max}$

1) $M_{\pi\pi}$ invariant $\pi\pi$-mass

2) $\alpha = (1-p_{min}/p_{max})q_{min}$ signed p-imbalance

3) $p_{tot} = p_{min}+p_{max}$ scalar sum of 3-momenta

Each mode has an individual mass distribution $p(M_{\pi\pi}) = G(M_{\pi\pi} - F(\alpha, p_{tot}))$

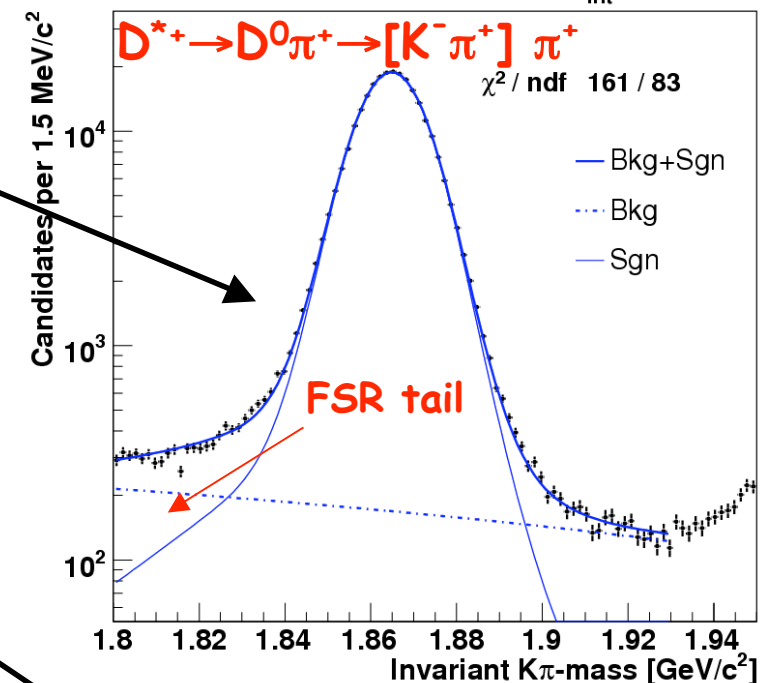This offers good discrimination amongst modes and between $K^+\pi^-/K^-\pi^+$

Mass lineshape and FSR
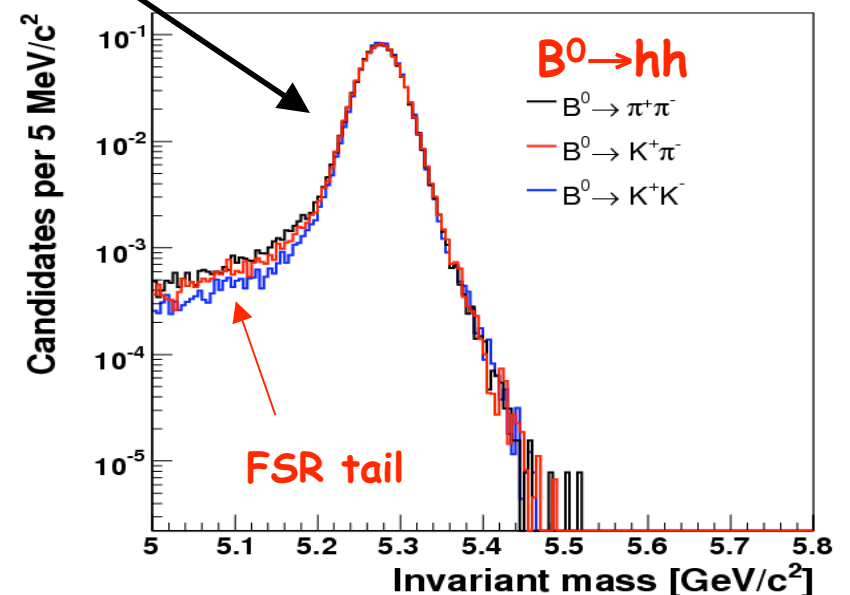

1) TEST on
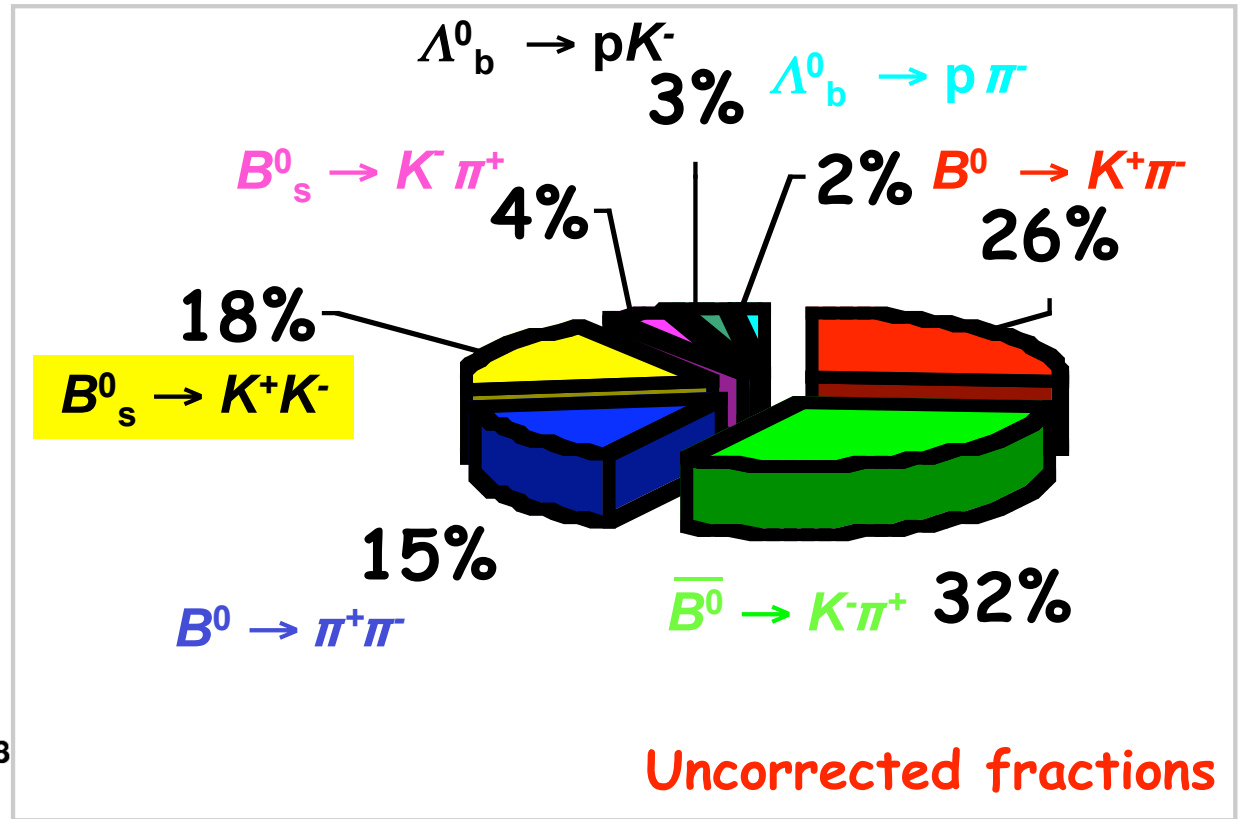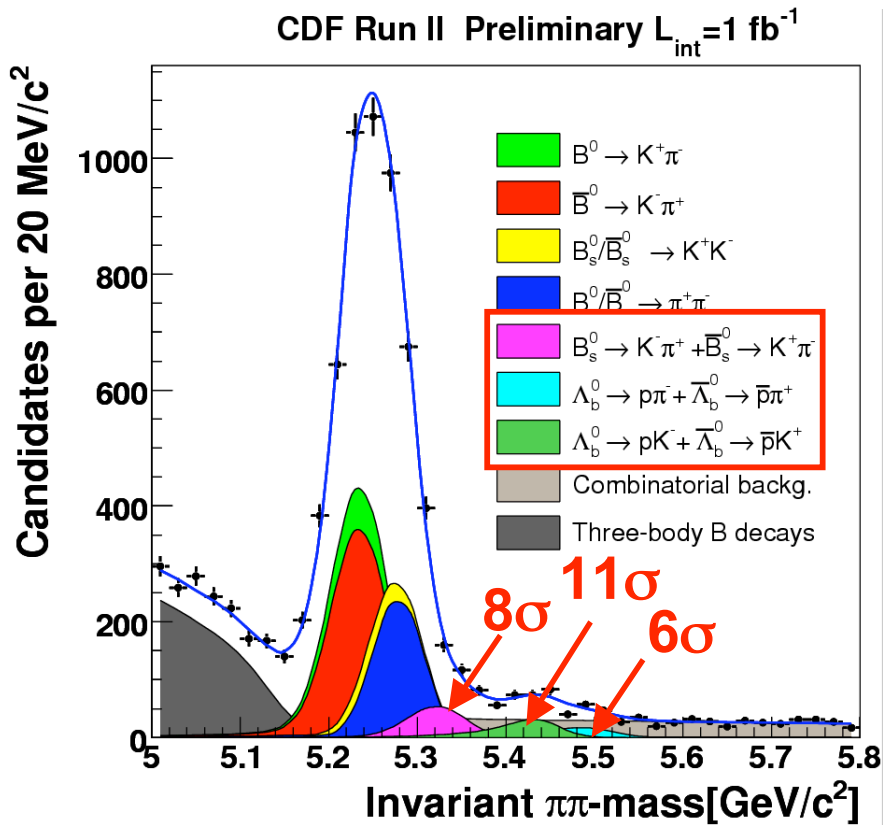$D^0 \rightarrow K^- \pi^+$

2) APPLY to
$B \rightarrow h^- h^+$

Results depend on assumed mass resolution
and details of the lineshape (rare modes
confuse with the tails of larger modes).
Need good control of non-gaussian resolution
and effects of Final State Radiation.
QED: [Baracchini,Isidori PL B633:309-313,2006]

Evidence for $B^0_s \rightarrow K^-\pi^+$

CDF Run II Preliminary $L_{int}=1$ fb^{-1}

Candidates per 20 MeV/c^2

- $B^0 \rightarrow K^+\pi^-$
- $\overline{B}^0 \rightarrow K^-\pi^+$
- $B^0_s/\overline{B}^0_s \rightarrow K^+K^-$
- $B^0/\overline{B}^0 \rightarrow \pi^+\pi^-$
- $B^0_s \rightarrow K^-\pi^+ + \overline{B}^0_s \rightarrow K^+\pi^-$
- $\Lambda^0_b \rightarrow p\pi^- + \overline{\Lambda}^0_b \rightarrow \overline{p}\pi^+$
- $\Lambda^0_b \rightarrow pK^- + \overline{\Lambda}^0_b \rightarrow \overline{p}K^+$
- Combinatorial backg.
- Three-body B decays

8σ 11σ 6σ

Invariant $\pi\pi$-mass[GeV/c^2]

$\Lambda^0_b \rightarrow pK^-$ 3% $\Lambda^0_b \rightarrow p\pi$

$B^0_s \rightarrow K^-\pi^+$ 4%   2% $B^0 \rightarrow K^+\pi^-$ 26%

18%

$B^0_s \rightarrow K^+K^-$

15%

$B^0 \rightarrow \pi^+\pi^-$ $\overline{B}^0 \rightarrow K^-\pi^+$ 32%

Uncorrected fractions

3 new rare modes observed

$$N_{\mathrm{raw}}(B^0_s \rightarrow K^-\pi^+) = 230 \pm 34\,(stat.) \pm 16\,(syst.) \quad (8\sigma)$$

$$N_{\mathrm{raw}}(\Lambda^0_b \rightarrow p\pi^-) = 110 \pm 18\,(stat.) \pm 16\,(syst.) \quad (6\sigma)$$

$$N_{\mathrm{raw}}(\Lambda^0_b \rightarrow pK^-) = 156 \pm 20\,(stat.) \pm 11\,(syst.) \quad (11\sigma)$$

BR(B⁰$_s$ → K⁻π⁺)

$$\frac{f_s \cdot BR(B_s^0 \to K^- \pi^+)}{f_d \cdot BR(B^0 \to K^+ \pi^-)} = 0.066 \pm 0.010 \ (stat.) \pm 0.010 \ (syst.)$$

$$BR(B_s^0 \to K^- \pi^+) = (5.0 \pm 0.75 \ (stat.) \pm 1.0 \ (syst.)) \times 10^{-6}$$

Previous limit (CDF) < 5.4 @90% CL

[Yu, Li, Lu, Phys.Rev. D71 (2005) 074026]

Alpha from CKM fit

pQCD

CDF

SOME PREDICTIONS:
QCDF [7 ÷ 10] ·10⁻⁶
[Beneke&Neubert NP B675, 333(2003)]
pQCD: [6 ÷ 10]·10⁻⁶
[Yu, Li, Lu, PRD71: 074026 (2005)]
SCET: (4.9±1.8)·10⁻⁶
[Williamson,Zupan:PRD74(2006)014003]
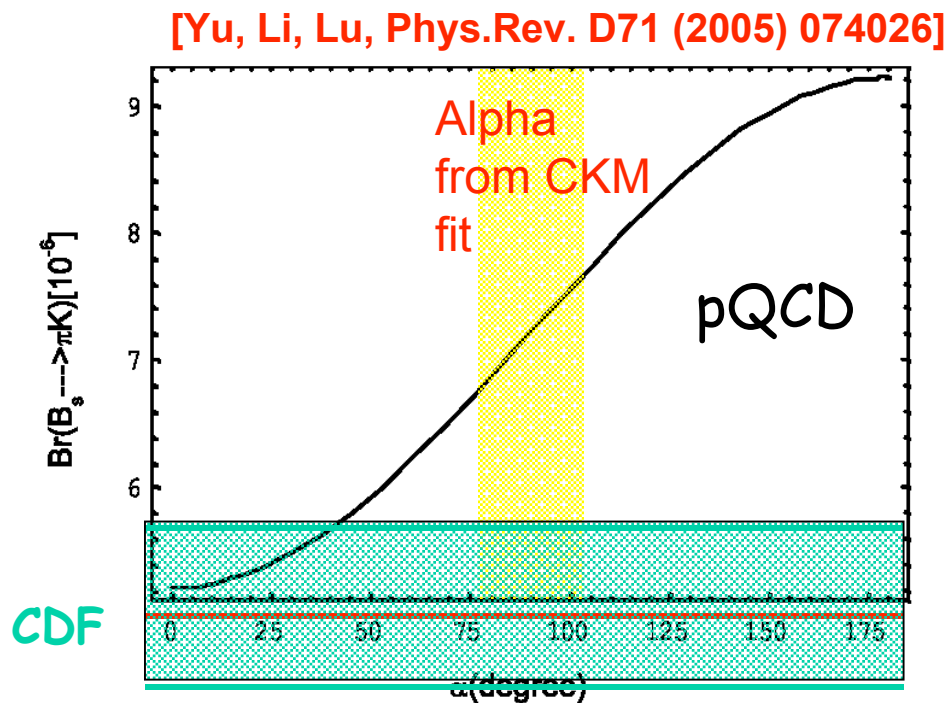
Large sensitivity to angle α/ϕ₂
[Gronau, Rosner, Phys. Lett. B 482, 71 (2000)]
[Yu, Li, Lu, Phys.Rev. D71 (2005) 074026]

Interesting dependence on CKM angles
Useful if it can be reliably predicted.

Direct CPV in $B^0_s \to K^-\pi^+$

Observation of this decay offers a unique opportunity of checking for the SM origin of direct CP violation, by means of a "sum rule":

$$\Gamma(\overline{B}^0 \to K^-\pi^+) - \Gamma(B^0 \to K^+\pi^-) = \Gamma(B^0_s \to K^-\pi^+) - \Gamma(\overline{B}^0_s \to K^+\pi^-)$$

later shown to hold under much weaker assumptions, in a paper titled:
"Is observed direct CP violation in $B^0 \to K^+\pi^-$ due to new physics ?
Check standard Model prediction of equal violation in $B^0_s \to K^-\pi^+$ "
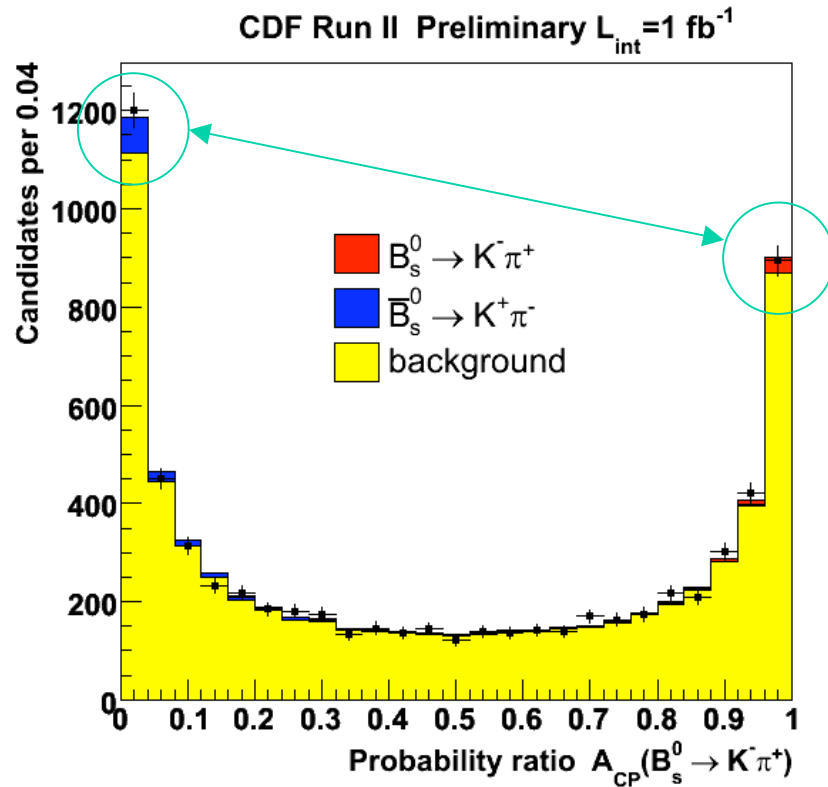**[Lipkin, Phys. Lett. B621:126, .2005]**

From our measured BR, we can predict DCPV using:

$$A_{CP}(B^0_s \to K^-\pi^+) = -A_{CP}(B^0 \to K^+\pi^-) \cdot \frac{\mathcal{B}(B^0 \to K^+\pi^-)}{\mathcal{B}(B^0_s \to K^-\pi^+)} \cdot \frac{\tau(B^0)}{\tau(B^0_s)}$$

Low **BR($B^0_s \to K^-\pi^+$)** implies large asymmetry: DCPV≅ **+37%**
Interesting case of large DCPV predicted under SM

Direct CPV in $B^0_s \to K^-\pi^+$

CDF Run II Preliminary L_{int} =1 fb⁻¹

Legend:
- $B^0_s \to K^-\pi^+$ (red)
- $\overline{B}^0_s \to K^+\pi^-$ (blue)
- background (yellow)

Y-axis: Candidates per 0.04

X-axis: Probability ratio $A_{CP}(B^0_s \to K^-\pi^+)$

$$A_{CP} = 0.39 \pm 0.15\text{(stat.)} \pm 0.08\text{(syst.)}$$

2.5 σ

$$\frac{\Gamma(\overline{B}^0 \to K^-\pi^+) - \Gamma(B^0 \to K^+\pi^-)}{\Gamma(B^0_s \to K^-\pi^+) - \Gamma(\overline{B}^0_s \to K^+\pi^-)} =$$

$$= 0.84 \pm 0.42\text{(stat.)} \pm 0.15\text{(syst.)} \; (\text{SM} = 1)$$

First measurement of DCPV in the Bs system

Sign and magnitude agree with SM predictions within errors ⇒ no evidence for 'exotic' sources of CP violation (yet)

**Exciting to pursue with more data**

BsKpi σ(ACP)/ACP

3 σ

5 σ

fb-1
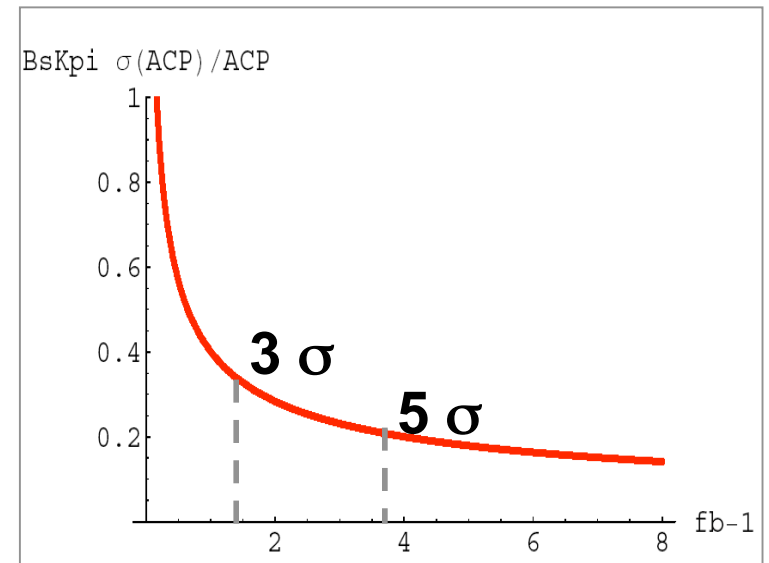
Prospects for $A_{CP}(B^0_s \to K^+ K^-)$

$$BR(B^0_s \to K^+K^-) = (24.4 \pm 1.4\ (stat.) \pm 4.6\ (syst.)) \times 10^{-6}$$

- We now have all ingredients for a
  time-dependent ACP measurement
  - Large samples (1300 ev/fb-1)
  - Tag Dilutions calibrated
  - x_s measured

- Can have $\sigma(A_{CP})$ ~0.2÷0.15 in runII
(translate to sensitivity on γ ~10 deg.)
This resolution allows some tests for NP.

- See example at right, about the
impact of SUSY on these asymmetries

Sigma ACP BsKK

(εD² = **5.3%**)

Resolution
uncertainty

fb-1
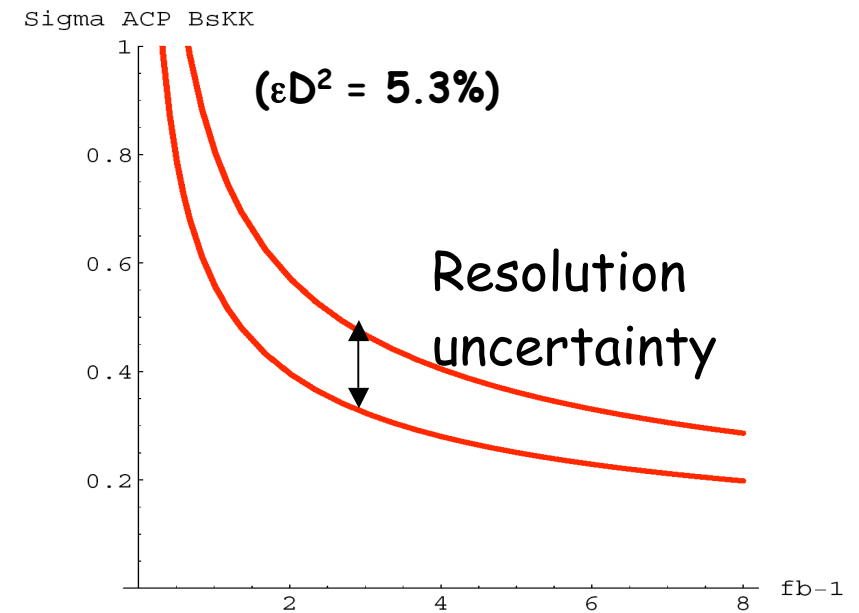
exp. resolution
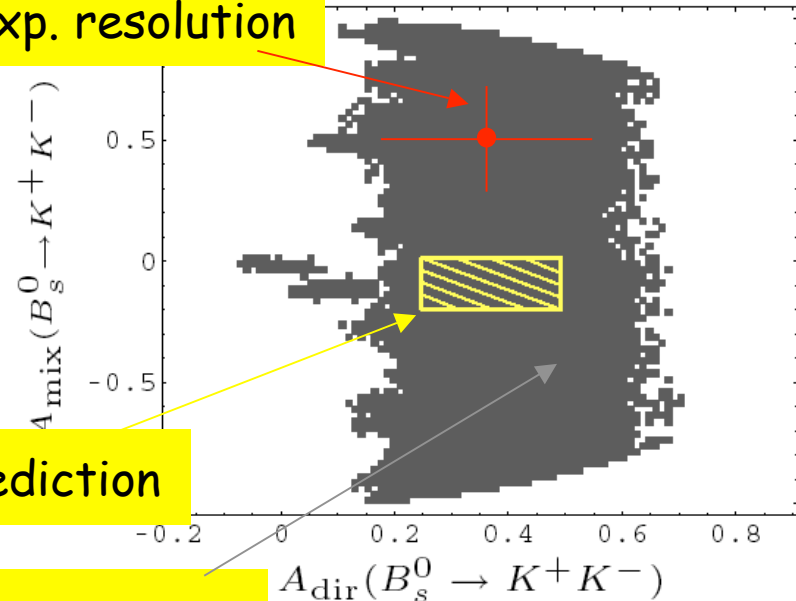
SM prediction

SUSY space

[Baek et al, hep-ph/0610109]

Measurements of
$\Delta\Gamma_s$ and ϕ_s

B⁰ₛ mixing and CP violation

EW Symmetry Breaking $\Rightarrow$ Weak $\neq$ Mass $\neq$ CP Eigenstates

$|B_H\rangle = p|B^0\rangle + q|\overline{B^0}\rangle$ $|B_{odd}\rangle = |B^0\rangle + |\overline{B^0}\rangle$

$|B_L\rangle = p|B^0\rangle - q|\overline{B^0}\rangle$ $|B_{even}\rangle = |B^0\rangle - |\overline{B^0}\rangle$

Observables

$\Delta m_s = M_H - M_L \sim 2|M_{12}|$ sens. to NP

$\Delta\Gamma_{CP} = \Gamma_{even} - \Gamma_{odd} \sim 2|\Gamma_{12}|$ not sens. to NP
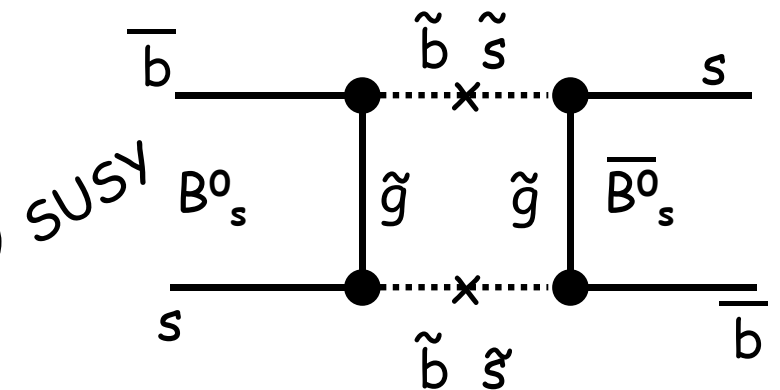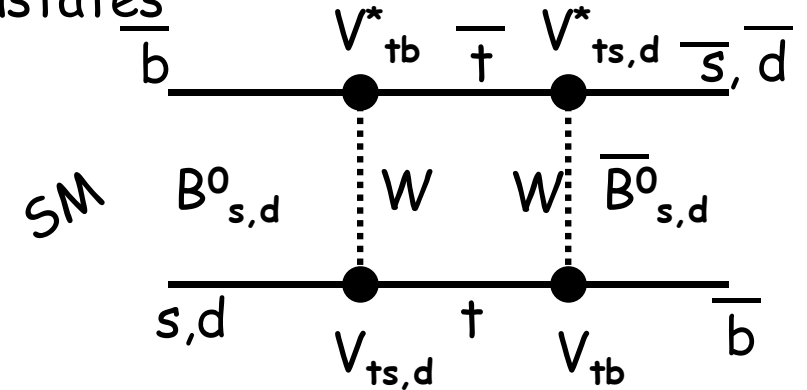
$\Delta\Gamma_s = \Gamma_L - \Gamma_H = \Delta\Gamma_{CP} \times \cos(\phi_S)$ very sens. to NP

($\phi_S = $ -0.5 - -0.8 in 4-gen models, hep-ph/0610385)

In the Standard Model

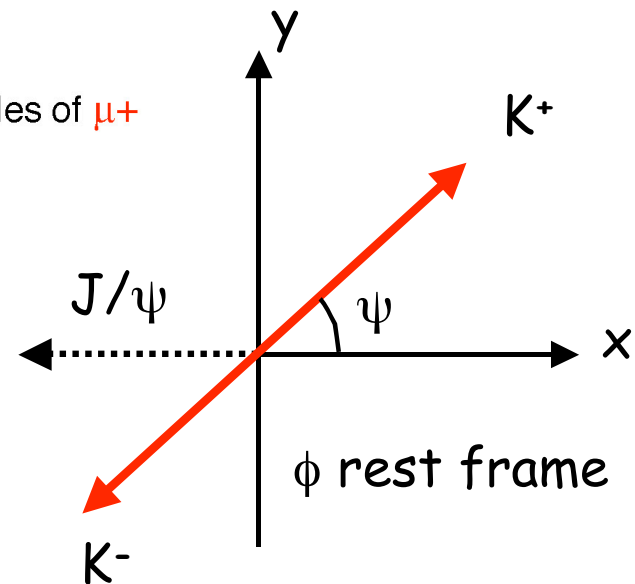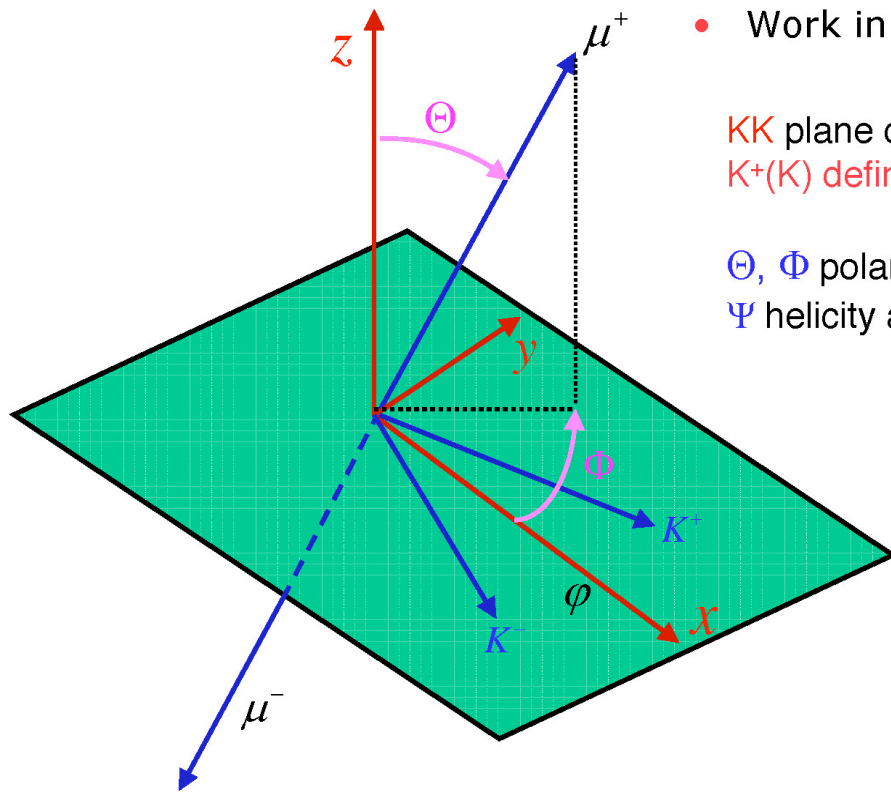- $\Delta\Gamma_s/\Delta m_s = O(m^2_b/m^2_t)$ (QCD)
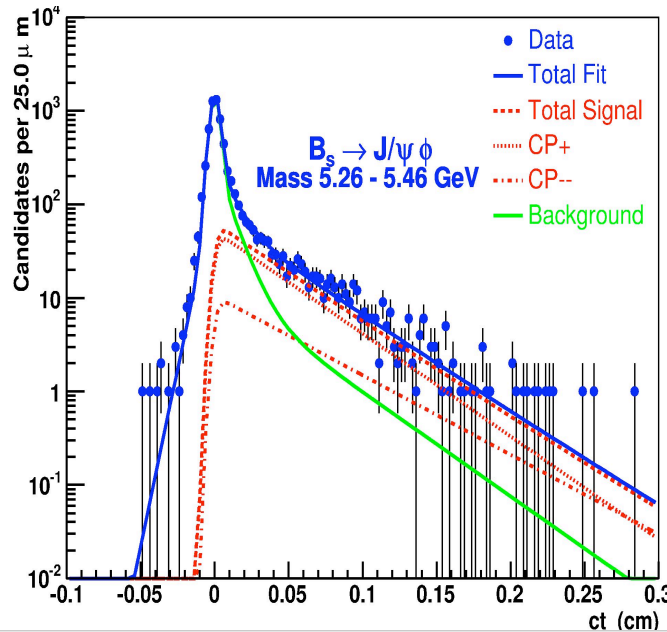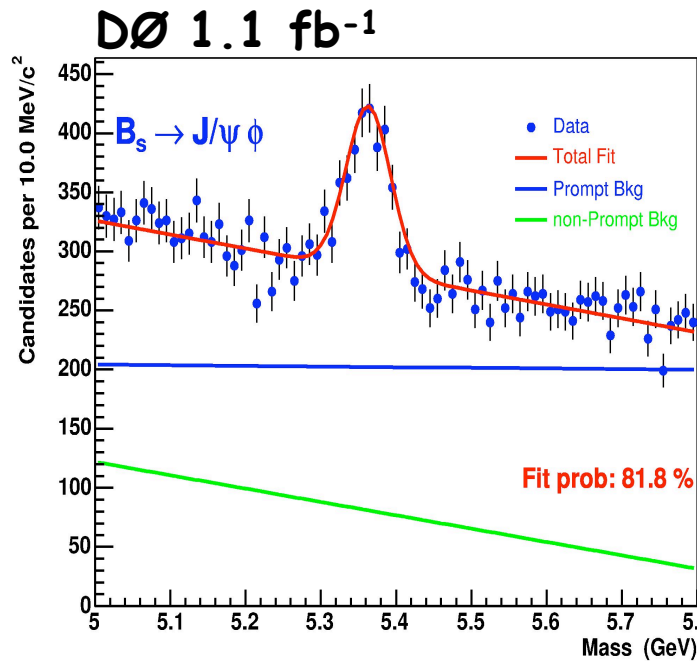- $\phi_s \sim (4.2 \pm 1.4) \times 10^{-2}$ (hep-ph/0612167)

$\Delta\Gamma_s$ and ϕ_s from $B_s \to J/\psi\phi$

- Directly measure lifetimes in $B_s \to J/\psi\phi$

  - Separate CP states by angular distribution and measure lifetimes

  - A_0 = S + D wave $\to$ P even

  - $A_{||}$ = S + D wave $\to$ P even

  - $A_\perp$ = P wave $\to$ P odd

  • $B_{s,Short,Light} \to$ CP even

  • $B_{s,Long,Heavy} \to$ CP odd

• Work in J/Ψ rest Frame

KK plane defines (x,y) plane
$K^+(K)$ defines +y direction

Θ, Φ polar & azimuthal angles of $\mu+$
Ψ helicity angle of ϕ $(K*)$
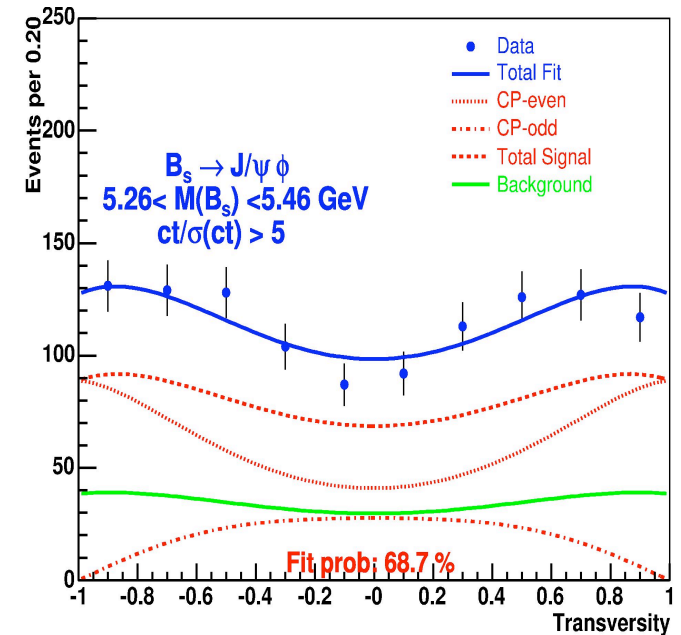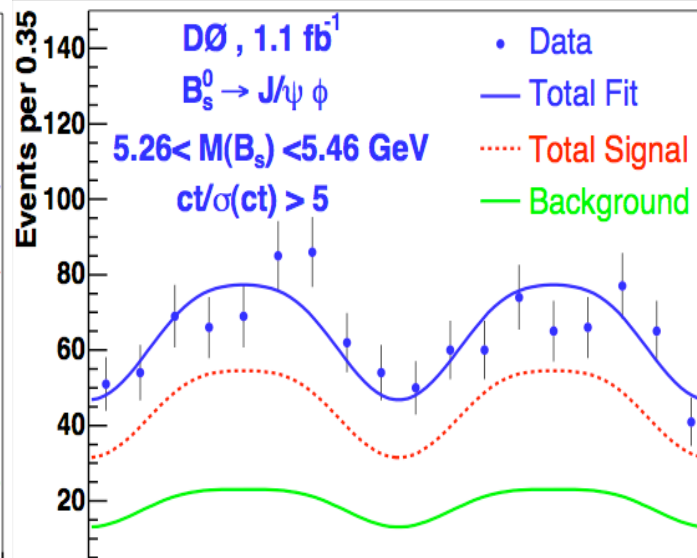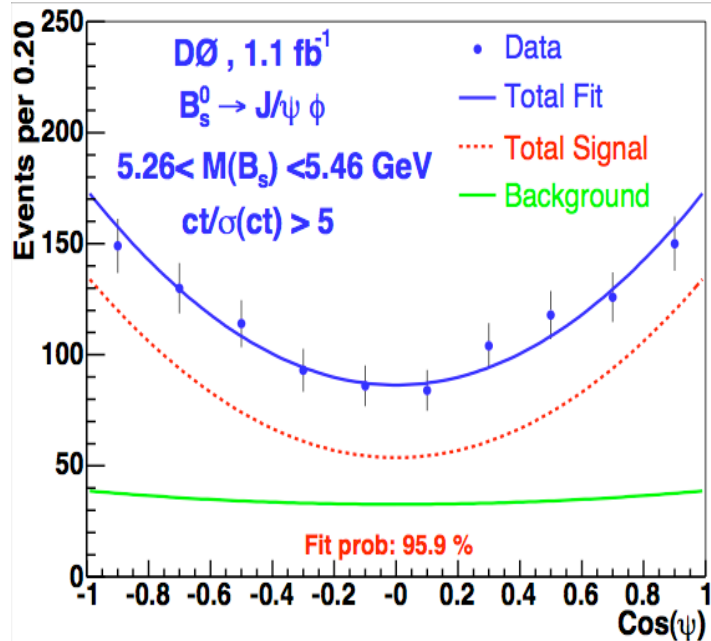

ϕ rest frame

$\Delta\Gamma_s$ and ϕ_s from $B^0_s \rightarrow J/\psi\phi$

-Simultaneous fit of mass, Lifetime, time dependent angular distributions.
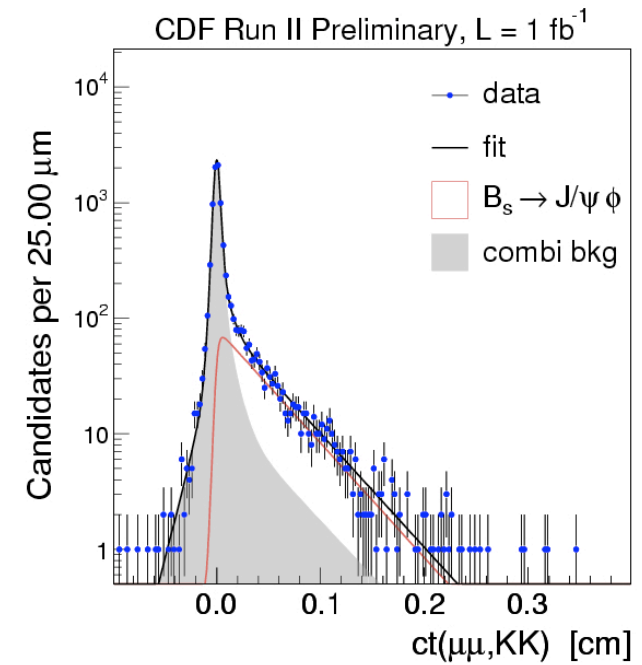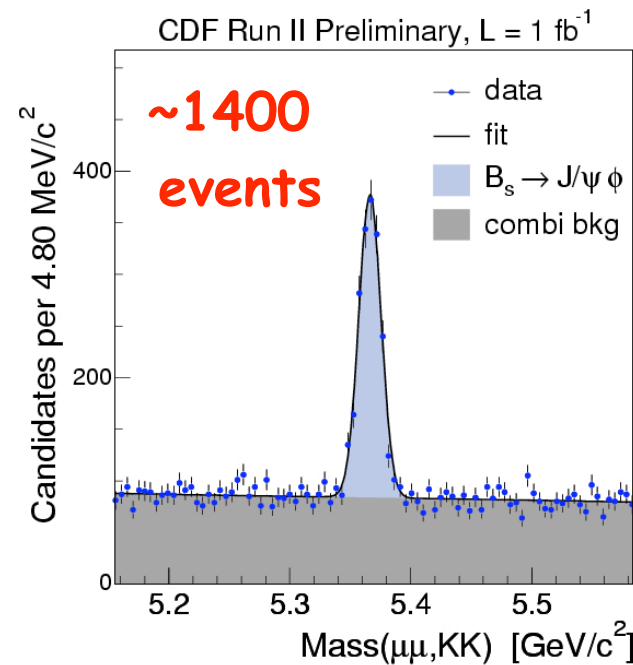-Extract $\Delta\Gamma_s$, ϕ_s , CP even, CP odd ampl, strong phases.

(DØ PRL 98, 121801 (2007)

Results for $\Delta\Gamma_s$ and ϕ_s

Observable	CDF (355 pb^{-1})	DØ (1.1 fb^{-1})	ϕ_s free
$N(B^0_s)$	203 ± 15	1039 ± 45	
$\Delta\Gamma_s$ (ps^{-1})	$0.47^{+0.19}_{-0.24}\pm 0.01$	$0.12^{+0.08}_{-0.10}\pm 0.02$	0.17 ± 0.09
$\langle \tau \rangle$ (ps^{-1})	$1.40^{+0.15}_{-0.13}\pm 0.02$	$1.52 \pm 0.08^{+0.01}_{-0.03}$	1.49 ± 0.08
ϕ_s	$\equiv 0$	$\equiv 0$	$-0.79\pm0.56^{+0.14}_{-0.01}$

CDF update on 1 fb^{-1} in progress

CDF Run II Preliminary, L = 1 fb^{-1}

~1400 events

data
fit
$B_s \rightarrow J/\psi\,\phi$
combi bkg

Candidates per 4.80 MeV/c^2

Mass($\mu\mu$,KK) [GeV/c^2]

CDF Run II Preliminary, L = 1 fb^{-1}

data
fit
$B_s \rightarrow J/\psi\,\phi$
combi bkg

Candidates per 25.00 μm

ct($\mu\mu$,KK) [cm]

Results for $\Delta\Gamma_s$ and ϕ_s

$BR(B^0_s \rightarrow D^{(*)}_s D^{(*)}_s)$
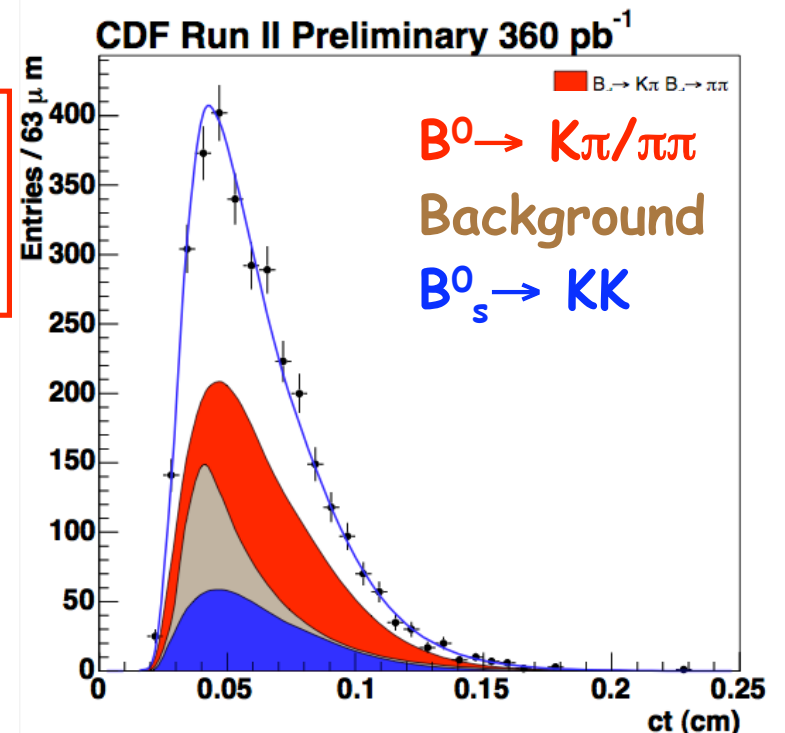$\quad\rightarrow \phi\mu\nu \quad \rightarrow \phi\pi$

$= (3.9 \pm 1.9 \pm 1.6\ )\%$

$\Delta\Gamma^{CP}/\Gamma = (7.9 \pm 3.8 \pm 3.1)\%$

hep-ex/0702049

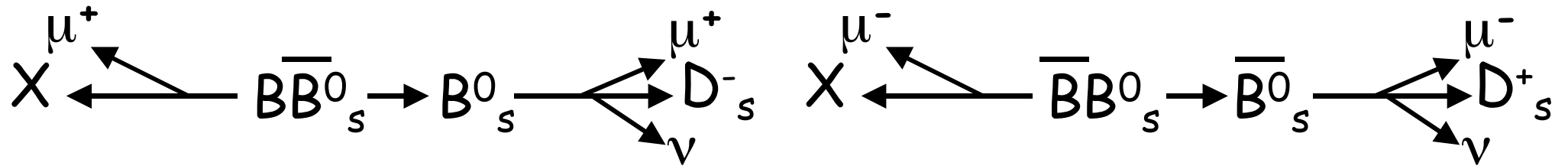$B^0_s \rightarrow$ KK

lifetime

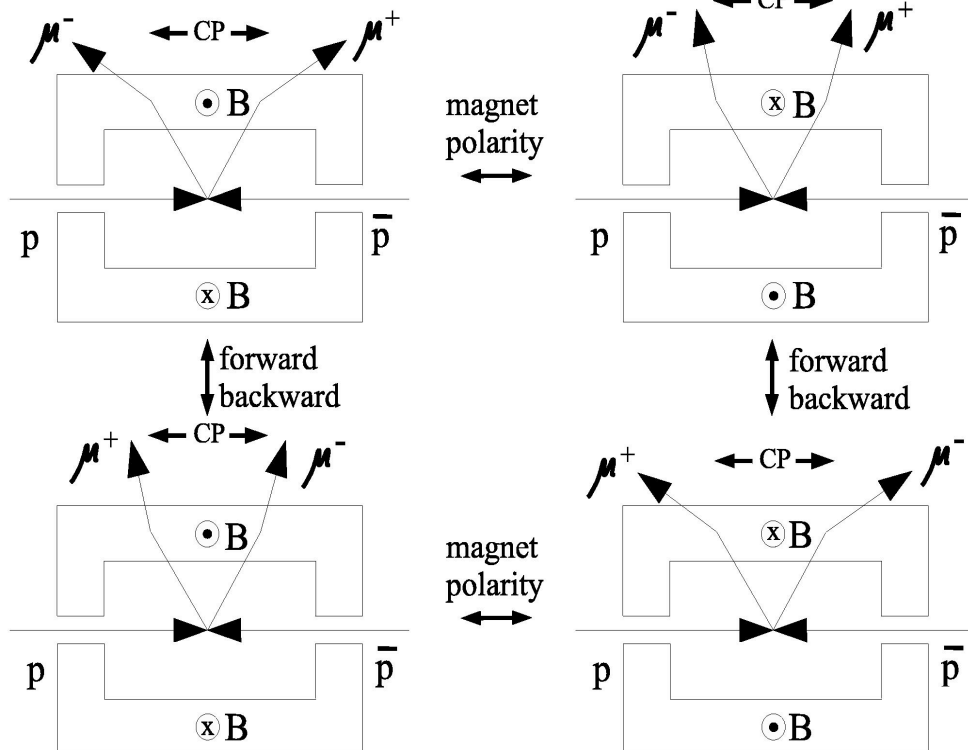$B^0 \rightarrow K\pi/\pi\pi$

Background

$B^0_s \rightarrow$ KK
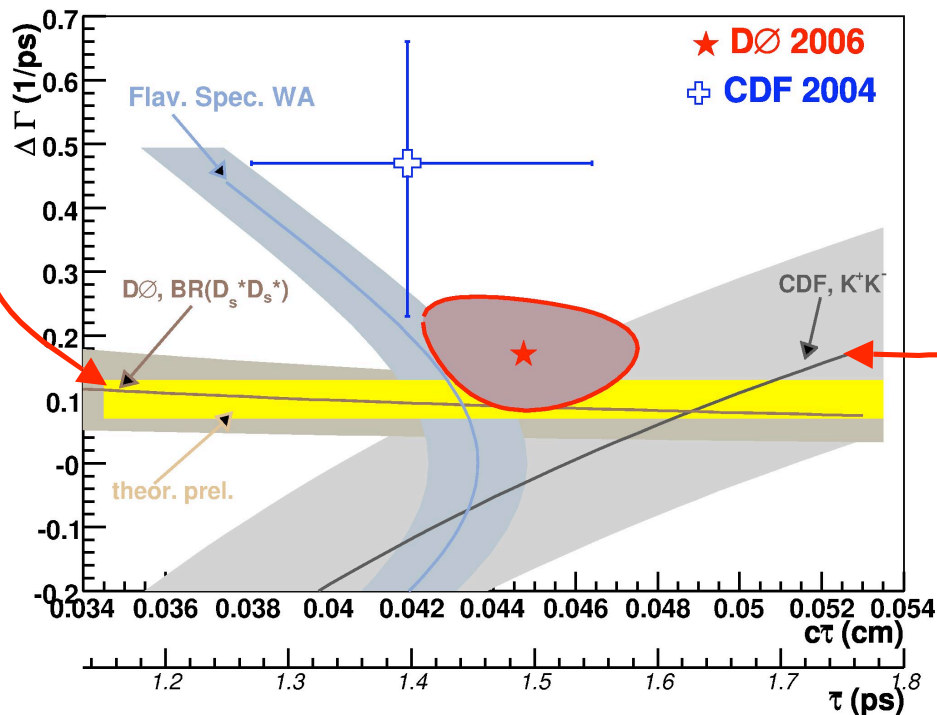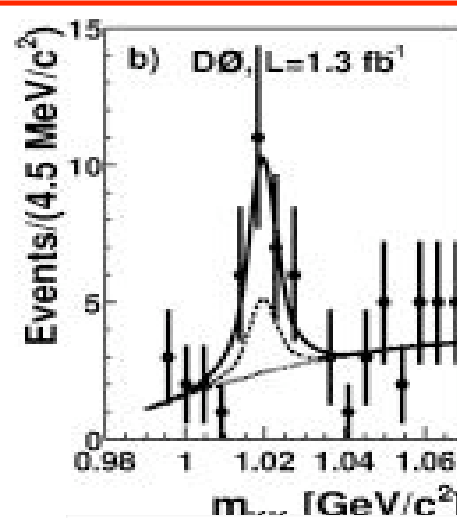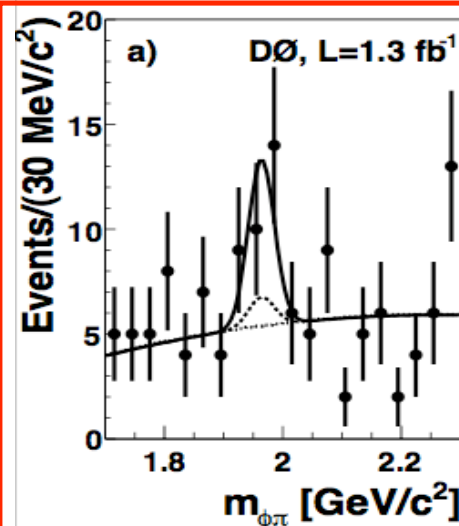
Dimuon charge asymmetry

Inclusive, tagged measurement sensitive to CP violation in B^0_s mixing

$$A^{\mu\mu}_{SL} = \frac{N(b\bar{b} \to \mu^+\mu^+ X) - N(b\bar{b} \to \mu^-\mu^- X)}{N(b\bar{b} \to \mu^+\mu^+ X) + N(b\bar{b} \to \mu^-\mu^- X)} = A^d_{SL} + (f_s Z_s / f_d Z_d) \times A^s_{SL} = (-0.92 \pm 0.44 \pm 0.32)\%$$

$0.70 \pm 0.07(\text{syst}) \pm (0.10)(\text{PDG})$

-0.0047 ± 0.0046 (B Factories)

$A^s_{SL} = (+0.0245 \pm 0.0193(\text{stat}) \pm 0.0035(\text{syst})$

Systematics reduced by regular flipping of DØ's B fields. PRD 74,092001 (2006)

Systematic uncertainties

Detector efficiency ratio on dimuons when toroid polarity is reversed

Significantly reduced by averaging over magnetic field polarities

Different $K^\pm$ interaction generates different $K^\pm \rightarrow \mu^\pm$ rates

Detector effects	0.00015
$e = \varepsilon+/\varepsilon-$	0.00018
Prompt μ + $K^\pm$ decay	0.00083
Dimuon cosmics rays	0.00010
Prompt μ + cosmic μ	0.00001
Wrong charge sign	0.00018
Punch-through	0.00001

Untagged charge asymmetry

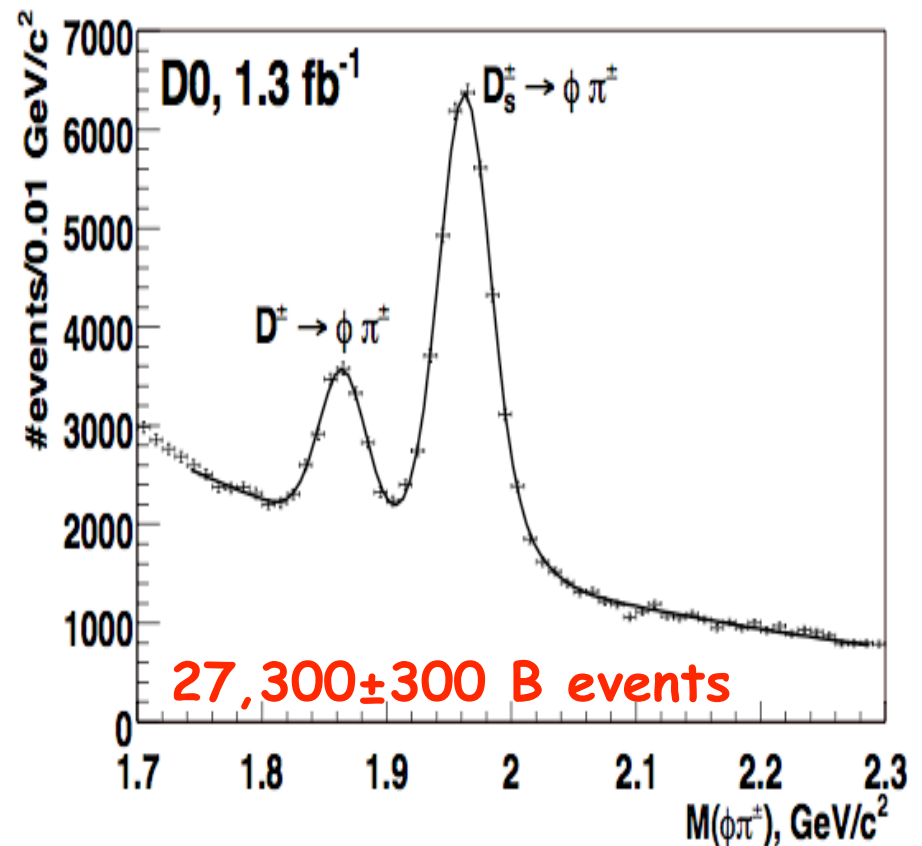Untagged asymmetry in $B^0_s \to \mu^+ D^-_s X$

$$D_s \to \phi\pi$$

$$A^s_{SL} = \frac{N(\mu^+ D^-_s) - N(\mu^- D^+_s)}{N(\mu^+ D^-_s) + N(\mu^- D^+_s)}$$

$A^s_{SL} = 0.0123 \pm 0.0097 \pm 0.0017$

SM prediction $\sim 10^{-5}$

Systematics:

- Different $\pi^\pm$ interaction with material,
- B^0_s fraction in the $\mu^+ D^-_s$ sample
- Fitting procedure (masses, peak widths)

D0, 1.3 fb^{-1}

$D^\pm_s \to \phi\pi^\pm$

$D^\pm \to \phi\pi^\pm$

#events/0.01 GeV/c^2

M($\phi\pi^\pm$), GeV/c^2

27,300$\pm$300 B events

Combining the two charge asymmetry measurements:

$A^s_{SL} = 0.0001 \pm 0.0090 \Rightarrow$ **$\Delta\Gamma_s \times \tan(\phi_s) = A^s_{SL} \times \Delta m_s = 0.02 \pm 0.16$ ps^{-1}**
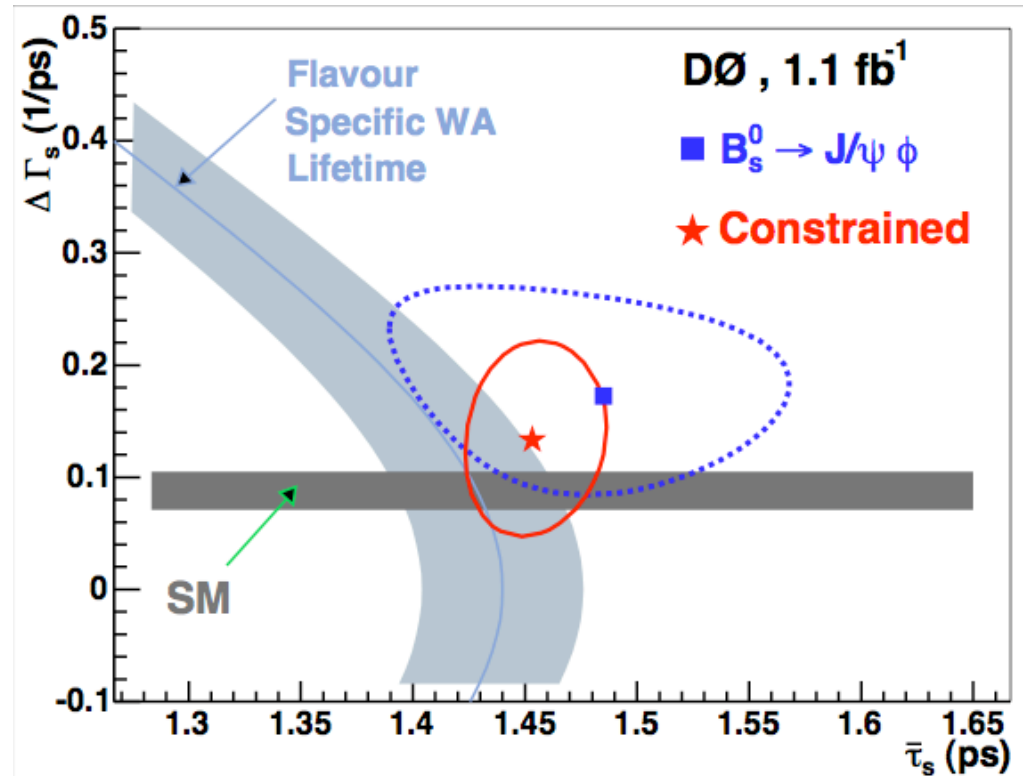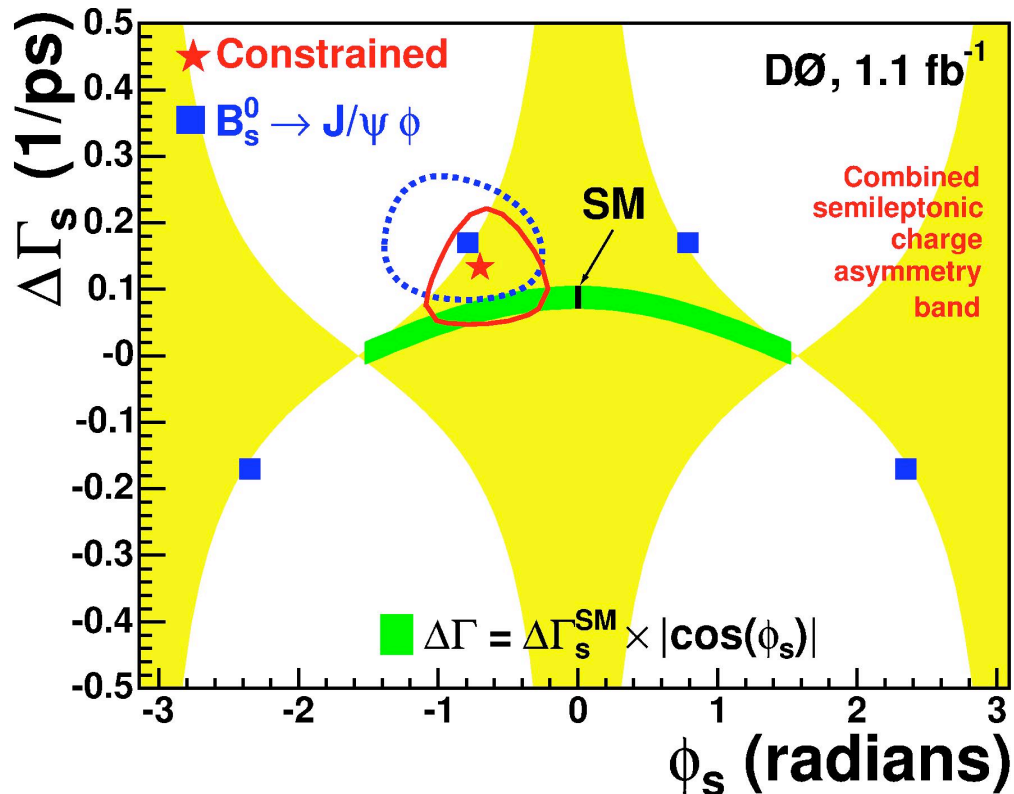
17.8 $\pm$ 0.1 ps^{-1}(CDF)

PRL 98, 151801 (2007)

Results for $\Delta\Gamma_s$ and ϕ_s

Repeat $B^0_s \to J/\psi\phi$ fit
- $B^0_s \to \mu\, D_s\, X$ asymmetry
- Dimuon asimmetry
- World average τ_{fs}

	DØ	SM
$\Delta\Gamma_s$ (ps^{-1})	0.13 ± 0.09	0.088 ± 0.017
ϕ_s	$-0.70^{+0.47}_{-0.32}$	$(4.2 \pm 1.4) \times 10^{-3}$

Conclusions

Both CDF and DØ are very active in the B^0_s sector

- Measurement of DCPV in $B^0_s \rightarrow K^-\pi^+$ (CDF)

- $\Delta\Gamma_s$ and ϕ_s measurements in $B^0_s \rightarrow J/\psi\phi$ (DØ/CDF)

- Dimuon/single muon charge asymmetry (DØ)

With the 2 fb^{-1} already on tape and the 8 fb^{-1} expected by 2009 we are confident to have many more and better results soon.